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Large Capacity and High-Data-Rate Phase-Change Disks

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Large-capacity phase-change disks permitting higher data-transfer rates have been developed for 0.85-numerical-aperture (*NA*) recording systems. Three methods to improve the recording data rate were examined. First, the recording layer was sandwiched by ceramic layers for the purpose of promoting nucleation. Second, signal properties were evaluated with a disk that had a so-called absorptivity-controlled structure. Third, these two methods were combined so that they functioned together in one disk. The disk structure was optimized separately for 640 nm and 407 nm wavelengths. With the disk designed for 640 nm wavelength, a user capacity of 9.2 GB and a user data-transfer rate of 50 Mbps were obtained. These quantities were 22 GB and 35 Mbps with the disk designed for 407 nm wavelength. (The disk diameter was 120 mm and the format efficiency was 80%.)

KEYWORDS: phase-change (PC) disk, high numerical aperture (*NA*), large capacity, high data-transfer rate, blue laser, absorptivity control, crystallization-promoting layer, Ge–Sb–Te, high-definition digital video recording

1. Introduction

Recently, post-VCR is a key phrase often heard in development discussions about rewritable optical disks. However, in order to make it possible to introduce an optical disk for consumer video application, we must overcome several barriers. For example, to store 3 h of 6.7 Mbps digital video data, the disk must have a user capacity of 9 GB. The data-transfer rate of the high-definition digital television signal will be around 24 Mbps and a user capacity of over 20 GB will be required for the disk to store a 2 h video.

Over several years, we have been pursuing a way to increase the storage capacity of optical disks based on a high numerical-aperture (*NA*) two-element lens.[1] In our previous works, we used GeSbTe-based four-layer disks, which were prepared through a reversed order sputtering process and protected by a 0.1-mm-thick cover layer.[2,3] Combining these four-layer disks and the two-element 0.85 *NA* lens, we achieved 8 GB[2] and 18 GB[3] user capacities with sufficient disk skew and cover thickness margins for 640 nm and 407 nm wavelength laser sources, respectively. However, these four-layer disks had one serious drawback: their limited data rate with which overwrite was completed.

As we increase the recording data rate, the time period for which the temperature of the material is kept above its crystallization point will decrease. This is the main factor that makes it difficult to realize high-data-rate overwriting with phase-change disks. In addition, a reduced spot size will give rise to a high spatial light energy distribution, which will also limit recording speed. Therefore, the main issue to be resolved in order to achieve higher data-transfer rates was insufficient time for nucleation and subsequent growth in the GeSbTe material system.

In this paper, we report results of experiments we conducted with the intention of increasing the data rates of phase-change disks based on the 0.85 *NA* two-element lens and 640 nm and 407 nm wavelength lasers. We investigated three possibilities which had been studied and reported by several authors, namely, the absorptivity-control method (referred to as ACM hereafter),[4–8] a quick crystallization method (QCM)[9,10] and an absorptivity-controlled quick-crystallization method (AQCM).[11] First, in ACM, the absorptivity of the crystal state of the recording layer was designed to be greater than that of the amorphous state. Second, in QCM, the GeSbTe layer was sandwiched by ceramic layers so that the nucleation at its interfaces was promoted. Third, in AQCM, the effectiveness of a combination of ACM and QCM was examined. We incorporated these three methods into our high *NA* technical context i.e., the reversed order deposition process followed by formation of a 0.1-mm-thick cover layer.

Advantages and disadvantages associated with each method were evaluated. We concluded that AQCM was the concept best suited to meet the high-data-rate target, as far as the GeSbTe material system was concerned. We tested several combinations of materials and disk structures within the AQCM concept and optimized them for our experimental conditions, namely, 0.85 *NA* and two wavelengths of 640 nm and 407 nm.

In the first half of this paper, the disk design for the wavelength of 640 nm and quick overwriting performances up to 50 Mbps are discussed. A tolerance analysis at 9.2 GB user capacity and 36 Mbps user data-transfer rate is also discussed.

In the second half of this paper, disk optimization for a 407-nm-wavelength laser and performances at 22 GB user capacity and 35 Mbps user data-transfer rate are presented. (In this article, the recording area is assumed to be 24 mm through 58 mm in radius and the format efficiency is assumed to be 80%.[12] We are discussing the user capacity and the user data-transfer rate here.)

2. Disk Optimization for 640-nm-Wavelength Lasers

2.1 *Speed limit of GeSbTe-based four-layer disks*

The maximum recording data rate of the four-layer disk used in our previous work[2] was about 18 Mbps. This limit was set by a decrease in erasability and an increase in mark distortion under quicker overwriting conditions. A numerical thermal analysis (Fig. 1) shows that increasing *NA* and/or increasing recording linear velocity have a negative impact on the time period necessary for crystallization. Yamada and coworkers proposed the thermally balanced structure to overcome this problem.[4,5] They recently pointed out that the combination of this structure and crystallization-promoting layers

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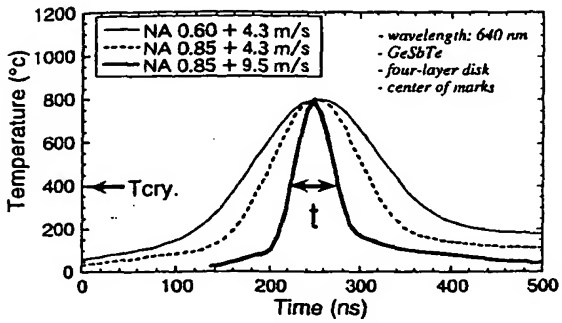

Fig. 1. Calculated results of temperature changes as a function of time. When a certain point of the recording layer experiences heat at the center of the laser beam, the profile of temperature changes varies according to the recording conditions; i.e., the numerical aperture (*NA*), and the disk rotation or the beam travelling speed. (The maximum temperatures that each calculation result reaches are normalized to 800°C.) The time period (t) in which the temperatures of the recording layer are held above the crystallization starting point (T_{cry}.), decreases as the *NA* and/or the beam travelling speed increase, while the wavelengths of the lasers are fixed to 640 nm.

was effective in further speeding up the overwriting process of the phase-change disk.[11]

2.2 ACM capabilities for red lasers

We first measured the recording speed of a disk that had a thermally balanced structure with a Si reflective layer,[7] whose cross section is illustrated in Fig. 2(a). The calculated absorptivity ratio was around 1.2 at the wavelength of 640 nm. Direct overwrite (DOW) performances of the disk are shown in Fig. 3. The dotted curves indicate overwrite jitters and the solid curves indicate changes in jitter values due to cross-write. The user data-transfer rate for overwriting was 36 Mbps with the track pitch and the linear density being 0.45 μm and 0.21 μm/bit, respectively, which corresponds to a 9.2 GB user capacity. While its durability against the cross-write was satisfactory, there was still room for improvement in its overwrite jitter values. The erasability of the disk, when 3 T signals were overwritten on 8 T signals, was around 26 dB, which caused its large jitter values.

2.3 QCM capabilities for red lasers

We investigated several dielectric or semiconducting material candidates to introduce the crystallization-promoting structure. These materials were SiN,[9] AlN, SiO_2, and SiC.[10] We found that SiC was the best in that it gave the smallest overwrite jitter at 36 Mbps. This result was due to an improvement in erasability from 26 dB to 32 dB that was brought about by the SiC layers. While the use of crystallization-promoting materials makes it easy to erase marks under a fast recording condition, it also has drawbacks. Among these is the problem of cross-write that has an immediate impact on narrowing track pitches. In our practical experiment, the disk with a track pitch of 0.47 μm did not exhibit any cross-write, but the disk with a track pitch of less than 0.45 μm proved to be slightly affected by it.

2.4 AQCM capabilities for red lasers

We combined the crystallization-promoting structure embodied by SiC and above mentioned thermally balanced structure with the Si reflective layer. A cross section of this seven-layer disk is illustrated in Fig. 2(b). ZnS–SiO_2, Si, ZnS–SiO_2, SiC, $Ge_2Sb_2Te_5$, SiC, and ZnS–SiO_2 were sputtered in this order onto a 1.1-mm-thick polycarbonate substrate surface on which pits and grooves were embossed. Finally, the disk was overlaid with a 0.1-mm-thick cover layer[2,13,14] and initialized.

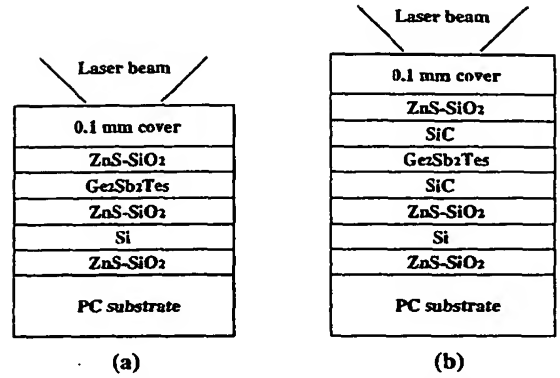

Fig. 2. Disk structures for red laser systems: (a) five-layer ACM disk, (b) seven-layer AQCM disk.

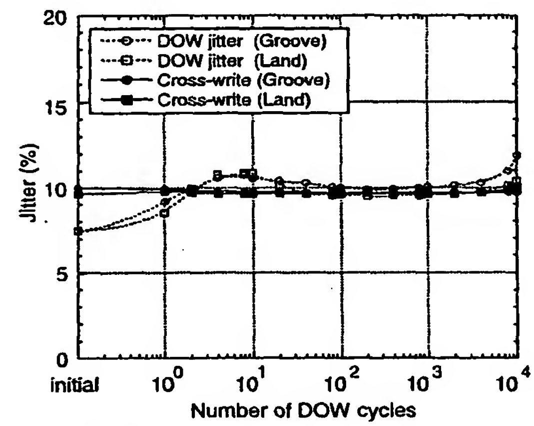

Fig. 3. DOW and cross-write performances of a red ACM disk measured under the conditions of a user data-transfer rate of 36 Mbps and a user capacity of 9.2 GB.

3. Signal Evaluation at 640 nm Wavelength: AQCM

We evaluated the read and write performances of the seven-layer disk using a 640-nm-wavelength laser diode. Experimental conditions are summarized in Table I. In our format, 0.45 μm and 0.43 μm track pitches correspond to 9.2 GB and 9.6 GB user capacities, respectively. In all the following results the effect of cross-talk is taken into account. The reading and writing of signals were completed with the laser beam traveling between the recording layer and the optics through the 0.1-mm-thick cover layer. Figure 4 shows DOW and cross-write performances at 9.6 GB user capacity and 36 Mbps user data-transfer rate. The 1–7 RLL random data was recorded once on both neighboring tracks of the object track and then DOW process was performed on the center track followed by the data-to-clock jitter measurement. Be-

Table I. Experimental conditions with a red LD.

Wavelength	640 nm
NA	0.85
Bit length	0.21 μm
Track pitch	0.45, 0.43 μm (9.2, 9.6 GB)
Recording	Land and groove
Modulation	1–7 code
Channel clock (@rec.)	68–94 MHz (36–50 Mbps)
Recording velocity	9.5–13.2 m/s
Format efficiency	80%

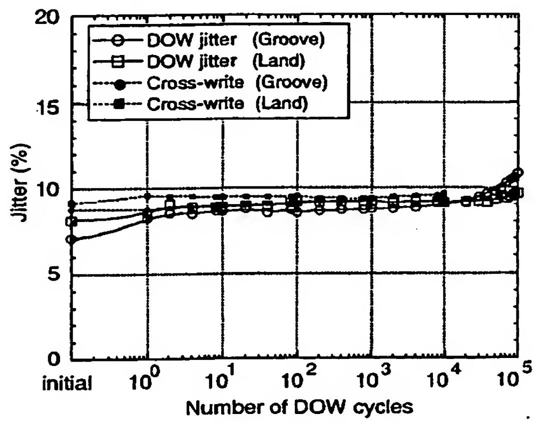

Fig. 4. DOW and cross-write performances of a red AQCM disk measured under the conditions of a user data-transfer rate of 36 Mbps and a user capacity of 9.6 GB.

fore the cross-write experiment, on the other hand, DOW had been completed 1000 times on the center track. No jitter bump was observed during the course of the DOW cycles and no significant jitter increase was observed during the repeated cross-writing procedure.

The laser power tolerances and cross-write tolerances of this disk are summarized in Table II. The maximum allowed jitter is assumed to be 13% in this table. With a 0.45 μm track pitch, the peak power and bias power tolerances after 1000 DOW cycles were around $\pm 15\%$. When the track pitch was 0.45 μm, the jitter increase due to the 1000 cross-write repeats carried out with 15% over power was less than 0.5%. However, with a 0.43 μm track pitch, it was 1% and 2% on the land and groove, respectively.

Additionally, the recording-data-rate range of a slightly modified seven-layer disk was examined, as described in Fig. 5. In the graph, the channel clock and the user data-transfer rate are indicated simultaneously on the *X* axis and jitter values on the land and groove after 1000 DOW repeats are plotted at each recording speed. Overwrite jitter remained at around 10% even when the recording data rate was raised to 50 Mbps. Figure 6 shows the DOW performances at 50 Mbps user data-transfer rate and 9.2 GB user capacity. (In this experiment, signals were read out after the disk rotation speed was adjusted so that a PLL with a 75 MHz self-running clock locked the reproduced signals for jitter measurement.)

The above-mentioned results prove that the inversely stacked GeSbTe-based AQCM disk, which was optically and thermally optimized for 0.85 *NA* objectives and 640-nm-wavelength laser sources, is one possible solution that meets the requirements mentioned in the introduction.

Table II. Power and cross-write tolerances at 36 Mbps.

Margin	Power margin		Jitter increase due to cross-write	
	Peak	Bias	$T_{p.} = 0.45\,\mu$m	$T_{p.} = 0.43\,\mu$m
Land	$\pm 15\%$	$\pm 18\%$	0%	1%
Groove	$\pm 15\%$	$\pm 18\%$	0.4%	2%

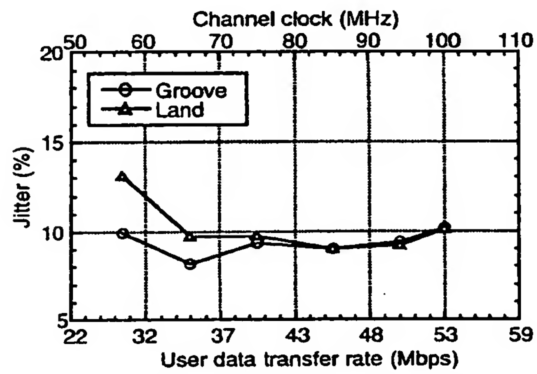

Fig. 5. Effective data-transfer rate margin of a red AQCM disk at a 9.2 GB user capacity.

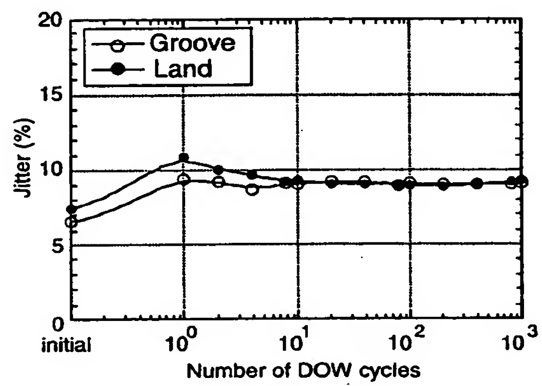

Fig. 6. DOW performance of a red AQCM disk measured under the conditions of a 50 Mbps user data-transfer rate and 9.2 GB user-capacity condition.

4. Disk Optimization for 407-nm-Wavelength Lasers

4.1 *Design change*

We have been optimizing our phase-change disk to allow it to function in the blue-wavelength region. We used a Kr+ laser with 407 nm wavelength in our media tester. The output of the Kr+ laser was modulated by an EO cell based on periodically poled $LiNbO_3$ crystal.[15] The rise and fall times of the modulation system were 1 ns and 2 ns, respectively and its maximum modulation frequency was about 80 MHz.

As described in the previous section, through the fabrication of the GeSbTe-based phase-change disk to meet the high data-transfer rate target based on a 640-nm-wavelength laser source, we found the AQCM concept. We expected that the AQCM strategy for increasing the speed of the overwriting process of phase-change disks would also be effective in the

blue-wavelength region. In order to put this strategy into practice, however, there were several issues we had to study beforehand. According to the wavelength dispersion, the optical constants of each material employed in the recording stack changed when we shifted from the red laser source to the violet one. For example, Si that previously enabled the adjustment of the absorptivity ratio between the amorphous and the crystal when the red coherent light was used had to be dismissed. Another mechanism with which the absorptivity ratio could be controlled had to be determined. In addition, a crystallization-promoting material that would lead to the optimum performance in the blue-wavelength region had to be found. A shorter wavelength has a considerable impact on thermal profiles, as shown in Fig. 7.

4.2 *Optimizing QCM for blue lasers*

Before attempting to apply AQCM, we first attempted to optimize the QCM structure for the blue laser. We applied SiC layers to the conventional four-layer disk for this purpose, as shown in Fig. 8(a), and optimized the thickness of each layer in order to evaluate the possible data-transfer rate.

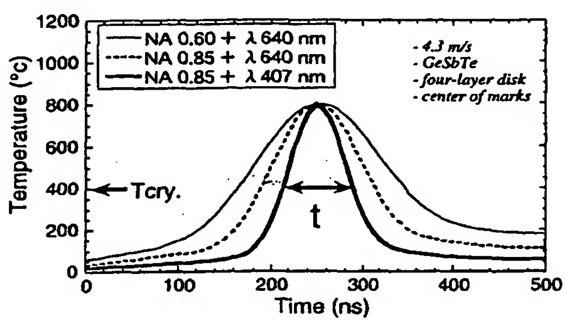

Fig. 7. Calculated results of temperature changes as a function of time. When a certain point of the recording layer experiences heat at the center of the laser beam, the profile of temperature changes varies according to the recording conditions; i.e., the numerical aperture (NA), and the disk rotation or the beam travelling speed. (The maximum temperatures that each calculation result reaches are normalized to 800°C.) The time period (t) in which the temperatures of the recording layer are held above the crystallization starting point (T_{cry}.), decreases as the NA increases and/or the laser source wavelengths decrease, while the beam travelling speeds are fixed to 4.3 m/s.

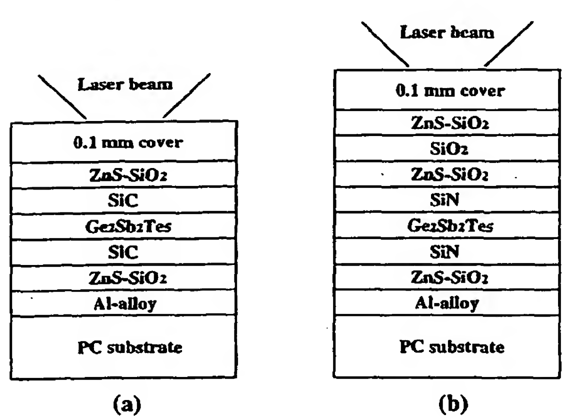

Fig. 8. Disk structures for blue laser systems: (a) six-layer QCM disk, (b) eight-layer AQCM disk.

Experimental conditions are summarized in Table III. The track pitch and the bit length were 0.30 μm and 0.13 μm, respectively, which corresponded to a 22 GB user capacity. The effect of the cross-talk was taken account of in all the following results. The DOW performances shown in Fig. 9 were obtained at 27 Mbps and 35 Mbps user recording rates. In this result, jitter values at 27 Mbps were below 10% even after 10,000 DOW repeats, both on the land and in the groove. (A similar result has been confirmed based on a GaN blue-violet laser diode at 27 Mbps and 22 GB.[16]) However, when we raised the data-transfer rate to 35 Mbps we observed significant jitter increases due to the lack of erasability. This result indicated that its speed limit was less than 30 Mbps, which was slightly lower than that of the QCM disk designed for a 640-nm-wavelength laser.

In order to raise the erasability further, we changed the crystallization-promoting material from SiC, in Fig. 8(a), to SiN, and also optimized the composition and the thickness of the Al-alloy reflective film. This optimization in QCM led to a jitter improvement of around 2% at 35 Mbps, as shown in Fig. 10.

4.3 *ACM for blue lasers*

Another issue we to be resolved was that the ACM structure with the Si reflective layer shown in Fig. 2(a), which was originally designed for 640-nm-wavelength lasers, did not work in the blue-wavelength region. Due to the wavelength dependence of optical constants of each material, it became difficult to find an adequate optical design. The calculated value of the absorptivity ratio (A_c/A_a) was around 1.0 at most for the wavelength of 407 nm. Instead, an optical

Table III. Experimental conditions with a Kr+ laser.

Wavelength	407 nm
NA	0.85
Bit length	0.13 μm
Track pitch	0.30 μm (22 GB)
Recording	Land and groove
Modulation	1–7 code
Channel clock (@rec.)	50, 66 MHz (27, 35 Mbps)
Recording velocity	4.3, 5.7 m/s
Format efficiency	80%

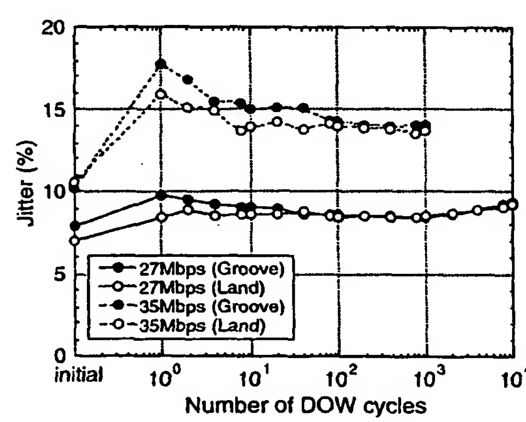

Fig. 9. Comparison in DOW performances between two recording speeds (i.e., 27 Mbps and 35 Mbps) of the blue QCM disk storing 22 GB user data.

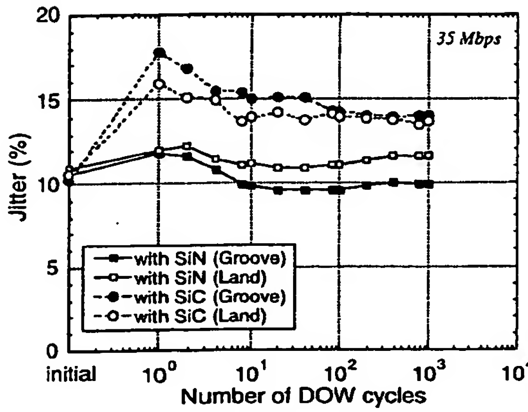

Fig. 10. Comparison in DOW performances between SiN and SiC used as the crystallization-promoting material for blue QCM disks.

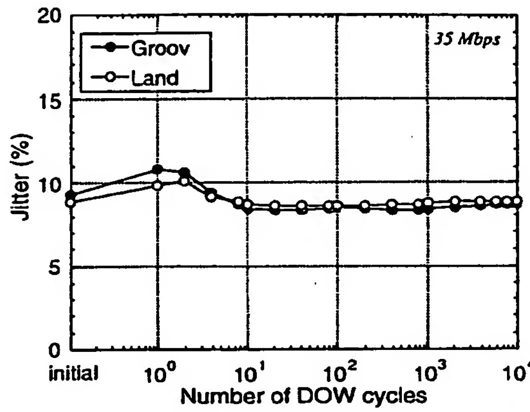

Fig. 11. DOW performance of a blue AQCM disk under a 35 Mbps user data-transfer rate and 22 GB user-capacity condition.

enhancement structure with a tri-layer dielectric film[8] was employed to control the absorptivity ratio. The tri-layer consisted of ZnS–SiO_2/SiO_2/ZnS–SiO_2 and gave an absorptivity ratio as large as around 1.5 at the wavelength of 407 nm.

4.4 *AQCM for blue lasers*

Finally, we combined the QCM structure with SiN layers and the ACM structure with the tri-layer dielectric film, as shown in Fig. 8(b), and optimized the thickness of each layer. Al-alloy, ZnS–SiO_2, SiN, $Ge_2Sb_2Te_5$, SiN, ZnS–SiO_2, SiO_2, and ZnS–SiO_2 were sputtered in this order onto a 1.1-mm-thick polycarbonate. The 8-layer disk was equipped with a 0.1-mm-thick cover layer and initialized. We also optimized the groove-geometry conditions of the substrate.

5. Signal Evaluation at 407 nm Wavelength: AQCM

Read and write performances of the new eight-layer disk by AQCM were examined at the user data-transfer rate of 35 Mbps and the user capacity of 22 GB. Other experimental conditions were the same as those listed in Table III. All the results were obtained taking into account the existence of cross-talk.

Figure 11 shows the data-to-clock jitter versus DOW cycles. The jitter values were improved compared with those obtained with the QCM and ACM disks. They remained below 10% even after 10,000 DOW repeats both on the land and in the groove. Figure 12 shows the eye patterns after linear equalization after 10,000 DOW repeats were completed on the land (a) and in the groove (b), respectively. Corresponding jitter values were 8.9% and 8.7% in the groove and on the land, respectively.

Skew margins were also evaluated. Figure 13 shows the result of tangential (a) and radial (b) skew margin analysis after 1000 DOW repeats. Both recording and reading were carried out under the same tilt conditions. When the jitter criterion was set at 13%, the tangential and radial skew margins were ± 0.45 degrees and ± 0.65 degrees, respectively. These practical skew margins at this high recording density were obtained because of the thin 0.1-mm-thick cover layer.

There are several issues remaining that must be considered in the future with the AQCM disk for the blue laser, for example, the suppression of cross-talk and cross-write and in-

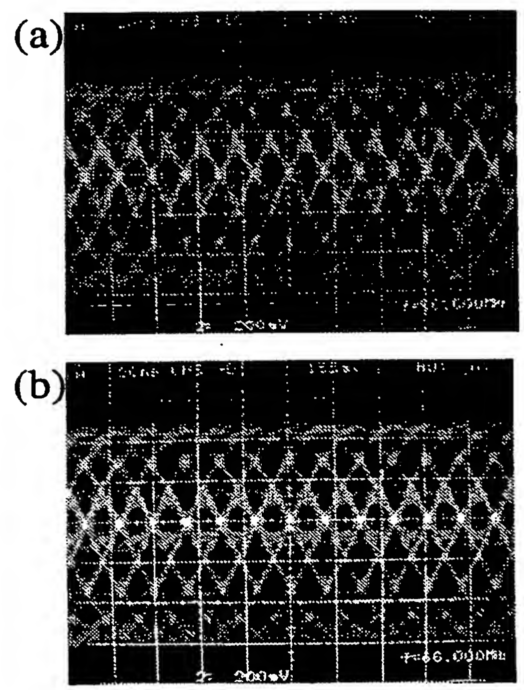

Fig. 12. Eye patterns for 22 GB and 35 Mbps recording after 10,000 DOW repeats: (a) on land, jitter = 8.9%, (b) in groove, jitter = 8.7%.

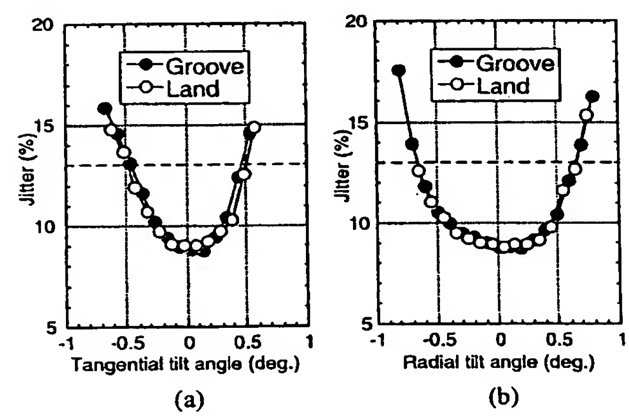

Fig. 13. Tilt tolerance measurement: (a) tangential, (b) radial.

creasing the speed of the DOW process further up to 50 Mbps. However, we believe that the experimental results discussed in this paper lead to the conclusion that the combination of the AQCM strategy and the 0.85 *NA* objective is one of the optical media candidates for a disk-based consumer video application.

6. Conclusions

We studied possible means of increasing the recording data rate based on the GeSbTe phase-change disks and the high *NA* two-element lens. By introducing an AQCM structure, we proved that direct overwriting at a 50 Mbps user data rate was practical at a 640 nm wavelength. Direct overwriting was also demonstrated at a 35 Mbps user data-transfer rate and 22 GB user capacity with a 407-nm-wavelength laser source. As far as the GeSbTe-based material systems are concerned, we believe that the AQCM concept is a promising strategy applicable to the design of a rewritable optical media for consumer video application.

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